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Recent developments in the measurement of precipitation elements from aircraft

by

M. P. Garrod

(Meteorological Office)

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

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1. Introduction

During the last few years the Meteorological Research Flight, for the purpose of cloud physics studies, has attempted to make measurements of many cloud parameters. Results up to 1955 have been reviewed in (1). Little progress in making one of the most important measurements, that of raindrop and precipitation elements (greater than 100 μ diameter), had been made previous to this time. It is the purpose of this report to describe the development of instruments for this purpose during the last two years and to present some preliminary results.

The instrumental development has now reached a stage where considerable data can be obtained very rapidly, and it is hoped later to produce more detailed studies of the various aspects outlined here.

For meteorological purposes, measurements of the development of precipitation elements, both solid and liquid, are important for the study of rainfall mechanisms and of the constitution of radar precipitation echoes. For aeronautical purposes a knowledge of the size, concentration and constitution of precipitation elements is important in studies of rain erosion, visibility in precipitation and airframe and engine icing, and the problem has therefore also received considerable attention from the Mechanical Engineering Department at the Royal Aircraft Establishment, Farnborough, with which close co-operation has been maintained in this work. The results of the Mechanical Engineering Department's laboratory studies have been described in (2).

2. Experiments with sooted screen techniques

2.1. From the outset several techniques, normally applicable for use at ground level, were considered for use in an aircraft. Many of these required complex equipment, e.g., those counting particles by electronic and optical methods required complex equipment which is difficult to install. Others, though simple, would provide only limited data after long periods in the air. The most promising method, and the simplest to install, was the sooted mesh screen technique described by Blanchard (3) which also included a method for calibration on the ground.

In this method a wire mesh, coated with soot produced by acetylene gas, is exposed horizontally in rain. A raindrop striking the gauze will not splash as if striking an impenetrable surface, but will break up after passing through the mesh, taking with it a small quantity of soot. As a result, a visible circular impression is left which bears a certain relation to drop size and velocity.

2.2. Before attempting any airborne trials it was necessary to establish what type of mesh was to be used, and the best form of soot coating. This was investigated by trying various combinations in a wind tunnel, and the final choice was a white silver plated mesh screen (80 strands per inch) and a coating of paraffin soot. No suitable coating was found for airspeeds exceeding 150 knots, but this, fortunately, was not a serious disadvantage. Incidentally, as a result of these experiments an excellent method for ground measurements was evolved, employing a screen with a first coating of magnesium oxide and a second of paraffin soot. A drop striking the screen completely removed the black soot, leaving the white magnesium oxide exposed in brilliant contrast to its surrounds.

2.3. A simple instrument was designed and constructed for use in the Hastings aircraft of the Meteorological Research Flight. (Fig.1) This instrument consisted of a tube four feet long and two inches in diameter. To one end was attached a screen holder and shutter mechanism operated by a Bowden cable. The tube could be clamped to an existing trolley, normally used for other sampling experiments, which was situated on the wireless operator's table. With the instrument fully extended the screen was exposed to an unobstructed airstream at about two feet from the skin of the aircraft. The complete installation for various samplers of this type has been described in (4).

2.4. A number of trial flights were made during the summer of 1955 to establish the capabilities and limitations of the sooted screen technique. In the first instance sampling was carried out in rain beneath cloud with varying airspeeds and rain intensity. It was found that the necessary exposure time, to obtain a good sample at 150 knots was five seconds or less, depending on rain intensity. Provided the airspeed did not exceed 150 knots the contrast obtained on the screen was sufficient for visual measurements, with the exception of marks less than 1 mm. diameter, the coarseness of the screen being too great for clear impressions. Examples are shown in Fig. 2a, 2b which indicate the clarity of the records for a considerable range of drop size.

A second series of flights was then made in rain-producing clouds. Results obtained were rather variable depending on cloud density and the quantity of rain. In many cases clarity of the record was lost, presumably due to cloud particles striking the screen in large numbers and partially removing the soot coating over the whole surface. However, this rarely caused complete loss of the record. Examples of screens exposed in cloud are shown in Fig. 2c, 2d. Rough outlines of snow and large ice crystals have also been detected by this method. (Fig. 2e, 2f)

2.5. The minimum size of impression on a screen for accurate measurements was about 1 mm., and this consequently limited the range of size measureable. To record drops of smaller diameter it was suggested that a sooted plate might be tried, as it was unlikely that much splashing would occur. A number of plates were exposed in very light rain, and the results were satisfactory. Some impressions were clearly visible having a diameter of about 250 microns, which suggested a true drop size less than this value. Above some unknown size splashing was occurring. Examples are shown in Fig. 2g, 2h of sooted plates exposed to varying drop sizes.

2.6. Before any research was possible using the sooted screen method it was necessary to obtain a calibration. This work was carried out by the Mechanical Engineering Department at Farnborough using a method similar to that described by Blanchard (2) known as the whirling arm. Sooted screens were firmly attached at each end of a horizontal rod four feet long, and rotated at the required airspeed by a 6 h.p. electric motor. The speed of the screens was obtained by means of a stroboscope. Drops of known size, calibrated by means of filter papers dusted with Rhodamine dye, were allowed to fall in the path of the screens until sufficient hits were made. The calibrations obtained for sooted screens and plates are given in Fig.3.

/3.

3. The aluminium foil technique

3.1. During the process of calibration the opportunity was taken by the Mechanical Engineering Department to test several other ideas which might be an advance on the sooted screen. It was found that if a thin aluminium foil was placed in front of a wire mesh screen, a raindrop hitting it at 100 knots or more left a circular indent and an inner circle formed by impressions of the gauze behind the foil. This inner circle had a diameter proportional to the true drop size.

It was at once apparent that a method had been evolved from which a continuous raindrop recorder could be designed, basically consisting of a continuous metal tape passing over a wire mesh screen behind an aperture. Provided the tape could be sufficiently long for several minutes running time, then it would show a vast improvement in sampling quantity as compared with sooted screens, apart from being a cleaner and more permanent record.

3.2. An impactor was designed and built late in 1955 at the Meteorological Research Flight (Fig.4). Other impactors based on the same principle have also been used in the Mechanical Engineering Department's aircraft, and also for experimental work with Bristol Britannia airliners. The basic design of the Meteorological Research Flight's instrument was similar to that used for the original sooted screen type. The instrument was operated automatically by a 24 volt electric motor, and the impactor head, shown also in Fig.4, contained two spools. The feed spool held about 20 feet of aluminium tape, 0.002 inch in thickness and one inch wide, one end of which was fed round rollers past an aperture to the second spool actuated by the electric motor. Behind the aperture a wire mesh screen was firmly soldered to a brass plate. The instrument was capable of giving a continuous running period of three minutes.

3.3. Calibration of the aluminium foil was carried out by the Mechanical Engineering Department at Farnborough, using the whirling arm method. The maximum speed attainable was about 150 knots, and a second method was used for higher speeds. This employed an aluminium bullet, the nose holding a small screen covered by the aluminium foil, which was fired by a compressed air gun at a drop suspended on a fine web (6). The bullet was decelerated by a succession of aluminium rings, clamped in a trough, whose internal diameter was slightly smaller than the outside diameter of the bullet. The sample obtained was undamaged by this process.

Calibration, using the gun, was carried out for speeds up to 300 knots. Fig.5 (inner circle diameter plotted against raindrop diameter) shows relevant calibration data for the Hastings aircraft, which normally flies at speeds of 150-200 knots.

3.4. During the first six months of 1956 a number of flights were carried out using this instrument. As a result, minor modifications were carried out, as follows:-

(a) The record on 0.002 inch thick tape was not very clear. 0.001 inch tape was substituted. (The Bristol Britannia instrument utilised tape 0.0005 inch thick.)

(b) It was found difficult to reload the instrument in flight, and the head was redesigned so that the spools could be easily separated from the instrument. The rollers, illustrated in Fig.4, were replaced by a smoothly curved brass plate, as the tape was breaking frequently, owing to sudden changes of direction round the rollers.

(c) The existing one-inch square aperture was too large for heavy precipitation conditions. This was reduced by a half, and the tape speed increased from about one inch per second to three inches per second.

/3.5.

3.5. During the latter half of 1956 further flights were made to investigate rain in and out of cloud, and also to record sizes and distribution of ice particles. Impressions obtained of small ice crystals were better than those of raindrops of similar size, but those of snowflakes were rather blurred. Examples of drizzle, moderate rain, and mixed snow and rain are shown in Fig.6. The apparent decrease in numbers of impressions across the tape record is due to a graded aperture used temporarily to establish the best width.

4. Preliminary results of flights during 1956 using the aluminium tape recorder

4.1. During 1956 records were obtained in about 50 flights concerned with large droplet content of cumulus and stratocumulus cloud, rain and snow particles in frontal cloud, coalescence rainfall and precipitation elements in cumulonimbus cloud. Each of these is a very large subject and it will only be possible here to present a brief summary of the preliminary measurements.

4.2. The distribution of large cloud droplets in cumulus and stratocumulus clouds

4.2.1. During traverses of non-precipitating clouds a number of drop impressions were found on the tape record which indicated the presence of drops considerably less than 500 microns, but probably more than 100 microns in diameter and therefore representative of the early stage of rain formation. To establish the lower limit of sizes recorded an experiment was set up in a wind tunnel. It was found possible to produce marks on a tape similar to those found in cumulus clouds. By comparing the tape record with a series of droplet samples, collected on oiled slides, it was evident that the smallest size causing a visible mark on the tape record was around 80-100 microns at 180 knots airspeed. As drop sizes of 500 microns were known to cause a very much larger impression, the size range of large drops recorded in cumulus and stratocumulus clouds was estimated to be between 100 and 250 microns. Droplets less than 80 microns diameter do not mark the foil used (0.001 inch thick). It may be possible to detect smaller sizes when thinner foil is used, and further work on these lines is contemplated.

4.2.2. A number of flights were carried out through convection clouds, and in all cases so far examined these drops were found at some levels. Further flights were made in stratocumulus layers, and examples are illustrated in Fig. 7. As far as can be concluded from the 15 flights so far made it appears that:-

(a) In Southern England, cumulus clouds having a depth of 1,000 feet to 3,000 feet can be expected to have mean concentrations of these larger droplets in the body of the cloud which may be as great as 1,000 per cubic metre but are usually less than 500. There is a distinct tendency for the base of the cloud to consist entirely of drops less than 80 microns diameter, while the top often shows the greatest number of drops in the 100-250 micron range.

(b) Active cumulus cloud having a depth of 4,000 feet to 6,000 feet, whether extending above the freezing level or not, show values up to 7,000 drops per cubic metre in the 100-250 micron range, and may include a few isolated 500 micron drops.

(c) Stratocumulus clouds having a depth of 1,000 to 3,000 feet give values up to 1,500 drops per cubic metre in the 100 to 250 micron range. Stratus cloud of this depth shows fewer, and sometimes none at all, greater than 80 microns. For thicker layers (i.e., 3,000 feet and over) the number of large droplets increases considerably.

As a rule the "concentrations" referred to above were the means over a flight path of about 1,000 feet, the starting point being chosen at random within the cloud. However, with some small cumulus clouds the whole width was sampled. This applies also to the concentrations shown in Fig.7.

/4.2.3.

4.2.3. A comparison is possible between these and the results on cumulus cloud sampling by the Meteorological Research Flight using the magnesium oxide technique (5). On these latter flights it was found that the average total number of cloud droplets per c.c. was about 100 to 300, with a maximum of 1,000 per c.c., or 10^9 per cubic metre. The maximum value so far found for drops in the 100-250 micron range by the aluminium foil method is 7×10^3 per cubic metre. Hence, for every drop exceeding 100 microns it appears that there are about 10^5 to 10^6 drops less than 100 microns in a medium sized non-precipitating cumulus cloud. It is also apparent that the chances of impacting a large drop in a cumulus cloud, using the magnesium oxide or oiled slide method (which samples only a few c.c. of air) is very remote, unless several hundred samples are taken. However, a few drops exceeding 100 microns were caught during the series of 150 magnesium oxide shots which were reported in (5). This report also pointed out that the drop size tends to increase with height in a cumulus cloud. Although this comment referred to sizes below 50 microns, it suggests a correlation with the increase in numbers of 100 to 250 micron drops with height found with the aluminium tape instrument.

4.3 The distribution of rain and snow particles in frontal cloud

The amount of data obtained so far on this subject is limited, and investigations of complete frontal systems have not yet been attempted. Sampling has been carried out on different occasions in various types of cloud associated with fronts, and to illustrate the type of information now obtainable abbreviated results of four of these are shown in Fig.8 and summarised below:-

(a) Nimbostratus. 23.1.56. In the zone sampled above the freezing level a considerable decrease in both sizes and numbers of snow particles occurred with increase in height, the greatest diameters, about 3 mm., being found at the freezing level. (The term diameter is used here to mean the estimated diameter of a circle having the same area as the impression of the ice crystal on the tape record. It is not known precisely how this is related to the dimensions of the crystal.)

Below the freezing level there is evidence of coalescence taking place, the maximum drop-diameter increasing from $1\frac{1}{2}$ mm. at 4,000 feet to $2\frac{1}{2}$ mm. at 2,000 feet. However, as samples were taken at random positions in an area 5 to 10 miles wide, variations at any level are inevitable over such distances. Consequently, comparison of one level with another for purposes of mathematical analysis should be made with caution.

(b) Nimbostratus. 11.12.56. No sampling was carried out above 6,500 feet on this flight. The figures suggest that in the zone below the freezing level some coalescence was occurring, the maximum drop-diameter increasing from $1\frac{1}{2}$ mm. at 5,000 feet to 2 mm. at 2,000 feet, while the numbers of all the remaining drops decreased substantially with decrease in height. These results are comparable with those of the previous case, showing a little less weight of precipitation at all three levels.

(c) Altostratus. 14.12.56. The figures obtained for the two levels sampled show an increase in the sizes of the ice particles with decrease in height, the total numbers at both levels being almost similar at around 5,000 per cubic metre. The largest size found was 1 mm. in diameter.

(d) Cirrostratus. 12.12.56. On this flight a predominance of very small ice crystals was found, but with small numbers with diameters of 250 microns. (Several of these crystals were caught and preserved on the aluminium foil owing to the very low temperature. Visual observation confirmed the estimate of the crystal size from the record.)

/4.4

4.4. The vertical distribution of drizzle and rain formed by the coalescence process

Two comprehensive flights have been carried out on occasions when rain was falling from cloud entirely below the freezing level. These are described separately below:-

4.4.1. 1.8.56. Cloud was solid from 1,500 to 7,500 feet, and the freezing level 10,000 feet. The aircraft climbed and descended twice through the cloud, and the mean values of drop counts calculated for each level are shown in Fig.9. No drops greater than 250 microns diameter were found, and there was a marked decrease in numbers with height from 16,000 to 1,000 per cubic metre.

4.4.2. 20.7.56. Drop sampling was carried out during the morning and the afternoon, one ascent being illustrated in Fig.10 which is somewhat similar to the three others which were obtained. The freezing level was 10,000 feet.

Drops in the 100-250 micron range decreased sharply with height from 6,000/cu.m. at 2,000 feet to less than 100 per cu.m. at 5,000 feet and above. Drops from $\frac{1}{2}$ mm. to $1\frac{1}{2}$ mm. were found at 2,000 feet, but were not found at all above 3,000 feet.

A comparison between these results and those of the cumulus cloud series shows an apparent reversal of the height distribution of 100-250 micron drops. Actual numbers are somewhat similar, but the greatest numbers are towards the top in a cumulus cloud, and at the bottom in a layered precipitating cloud. This aspect will be investigated further as data accumulate.

4.5. The distribution of rain and snow in cumulonimbus clouds

Five detailed flights have been made in cumulonimbus clouds, all in connection with the "Britannia" icing problem late in 1956. On these flights sampling was carried out every 500 feet over cloud depths of 10,000 feet or less, and it has been necessary to abbreviate these results to make a comprehensive picture. Owing to the rapid development of these clouds in space and time, samples at the same level varied considerably. The quoted values are those of the greatest concentrations encountered.

Considerable difficulty has been encountered in the analysis of the records for occasions of heavy snow. Figures quoted should be taken with some reserve, a factor of 2 being the probable error in the number of snowflakes per cubic metre. Where snow particles do not exceed 1 mm. in diameter the results are of greater accuracy.

The results of these flights are illustrated in Fig.11, which shows clouds in three different states. Each one is discussed separately below:-

4.5.1. Small cumulonimbus. Three flights have been made through cumulonimbus clouds with tops at or below 15,000 feet. Mean maximum values are shown of snow or supercooled drops between 5,000 and 12,500 feet. Snowflakes were found with diameters up to 3 mm. at the lower levels, while 2 mm. ones were found throughout the cloud. Supercooled drops of 1 mm. diameter were found in one case up to 7,500 feet (-10°C). Maximum numbers of small ice crystals were about 20,000 per cubic metre at 10,000 feet, with considerably smaller values at lower levels.

4.5.2. Large cumulonimbus. Only one flight has been carried out through a cumulonimbus of great vertical extent. In this case, on 4.10.56, the top was 25,000 feet or more and sampling was restricted to levels between 12,500 and 20,000 feet. Snowflakes of 2 mm. diameter were found at all levels, but none greater. On several runs at around 17,000 and 18,000 feet (-30°C) impressions were found on the tape record which were similar to those made by raindrops of about 1 mm. diameter. As considerable turbulence and vertical motion were experienced in the cloud, it is reasonable to assume these were supercooled drops. Ice crystals in the 100-250 micron range

showed a maximum at 20,000 feet of 45,000 per cubic metre, by far the most as yet encountered, and generally the numbers throughout the levels examined were much more than has been found in any other cloud type.

4.5.3. Old cumulonimbus anvil. One example only is available, which was recorded on 4.10.56. The cloud had probably been in existence for several hours, and at the time of sampling extended from 12,000 to 20,000 feet, over a wide area. The largest ice crystals (aggregates) were about 500 microns in diameter at 15,000 feet, and at 19,000 feet only the smallest ice crystals were evident. This is somewhat similar to the results for frontal cloud, except that 1 mm. snowflakes were not evident, presumably having fallen out earlier during the decaying stage of the main bulk of the cumulonimbus cloud.

5. Conclusions

An instrument has been developed for continuously recording in an aircraft the size distribution of raindrops. It has also been established that it can be used for determining the distribution and size of ice particles in the atmosphere, and the calibration for this purpose is now almost complete.

This instrument can be used in research into many aspects of cloud physics which have until now been insufficiently studied, such as the variation of rain and snow spectra in frontal and shower clouds, and their relation to radar echoes. Measurement of diameters of cloud drops at the higher end of the spectrum is possible, and perhaps with certain improvements smaller cloud drops may be included.

Acknowledgments

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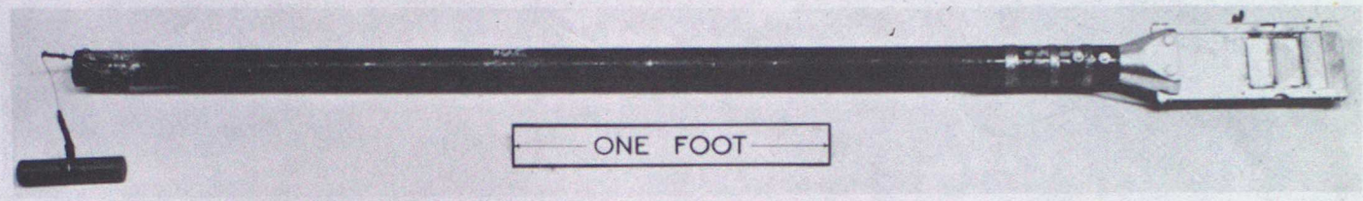
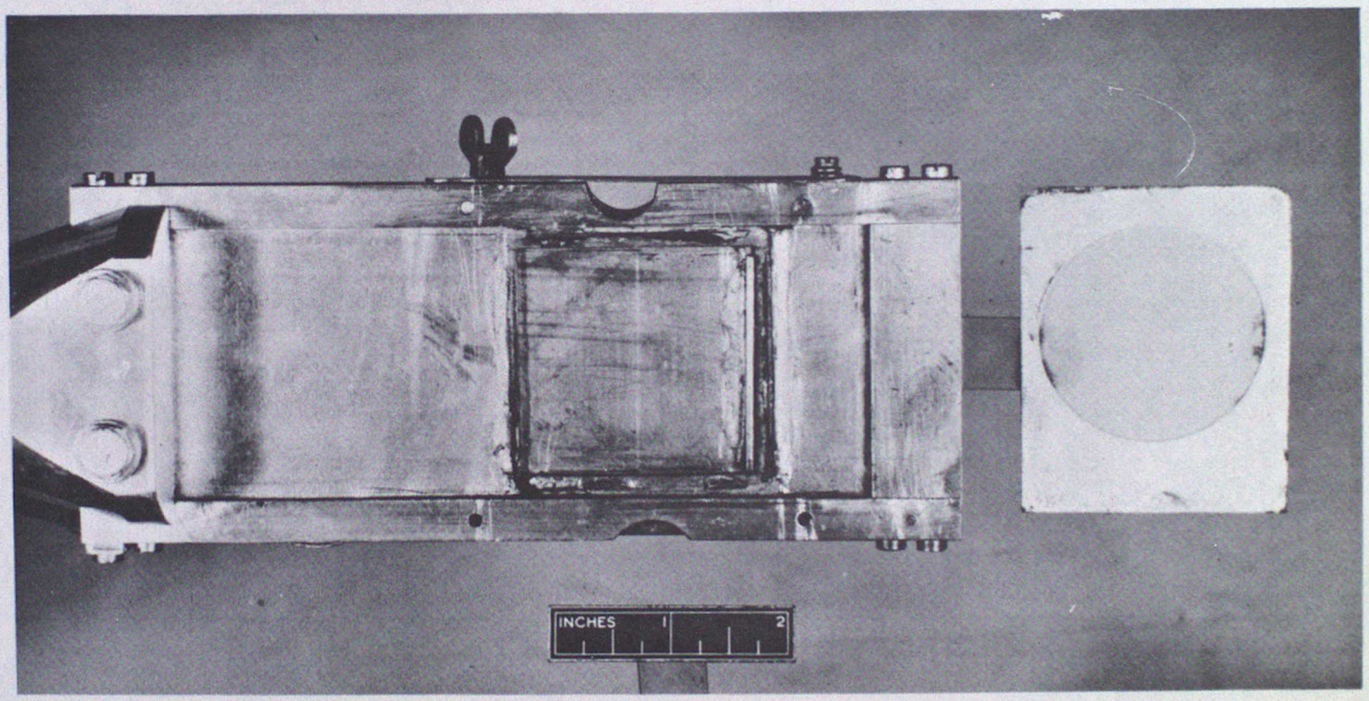
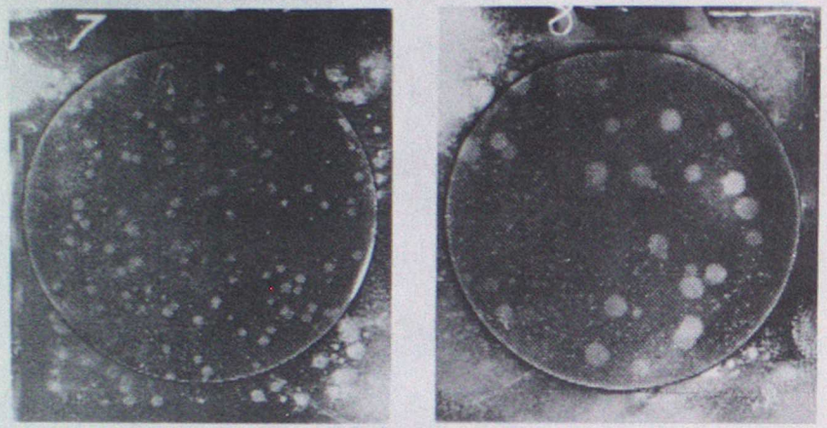
FIG. 1

SOOTED SCREEN TYPE
RAINDROP IMPACTOR.



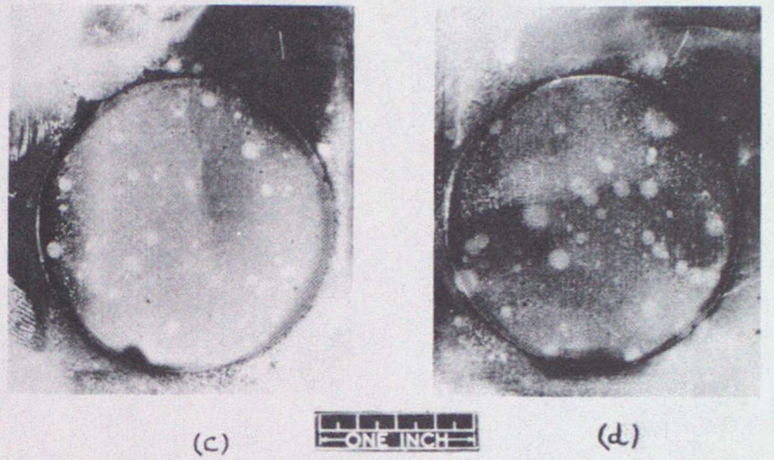
IMPACTOR HEAD AND SCREEN.





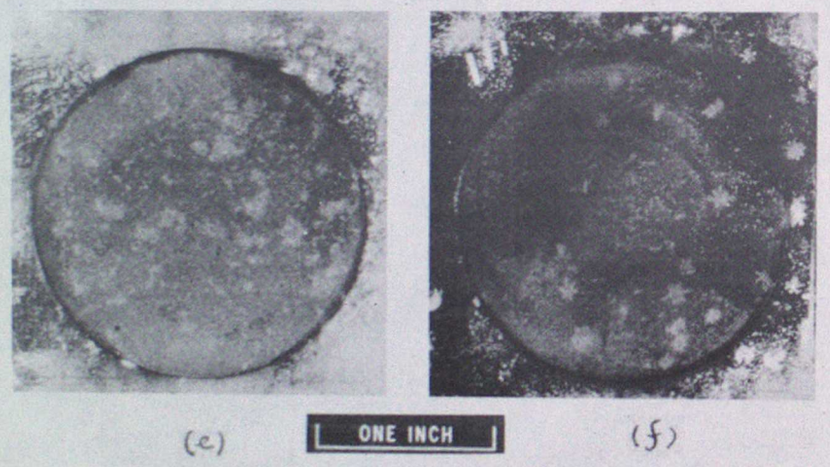
(a) (b)

RAIN SAMPLES IN CLEAR AIR



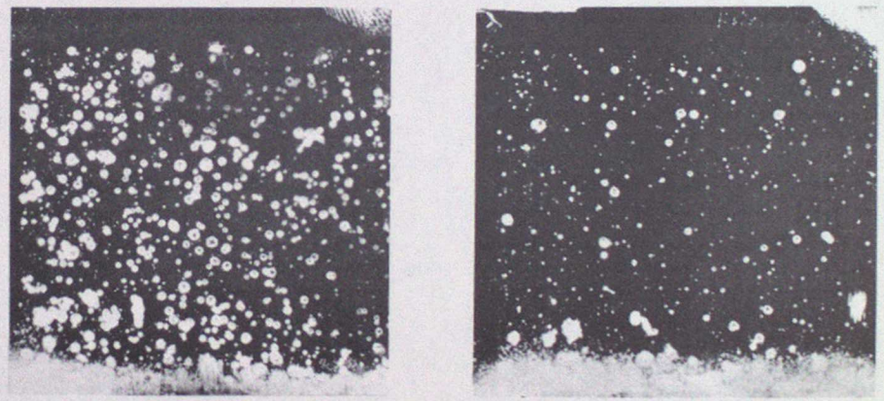
(c) (d)

RAIN SAMPLES IN CLOUD



(e) (f)

SNOW SAMPLES IN CLOUD



(g) (h)

SAMPLES OF LIGHT RAIN ON SOOTED PLATES

FIG. 2

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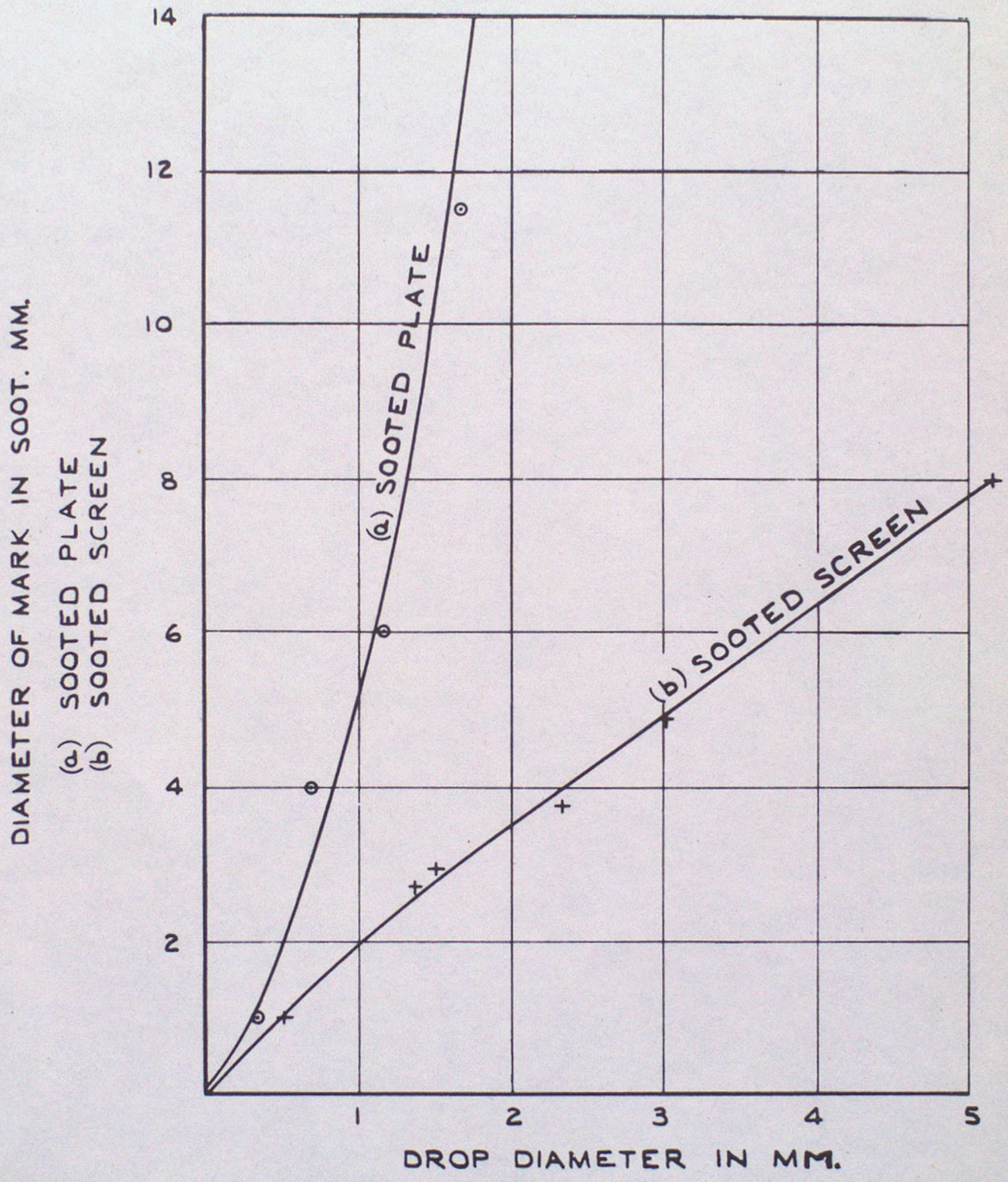
FIG. 3.



(REPRODUCED FROM T.N. M.E. 223.)

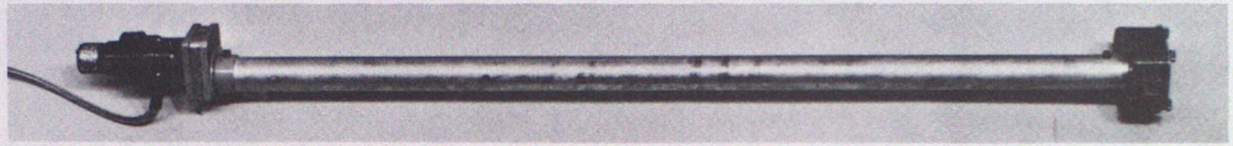
FIG. 3. CALIBRATION CURVES FOR SOOTED SCREEN AND PLATE AT 130 KNOTS.

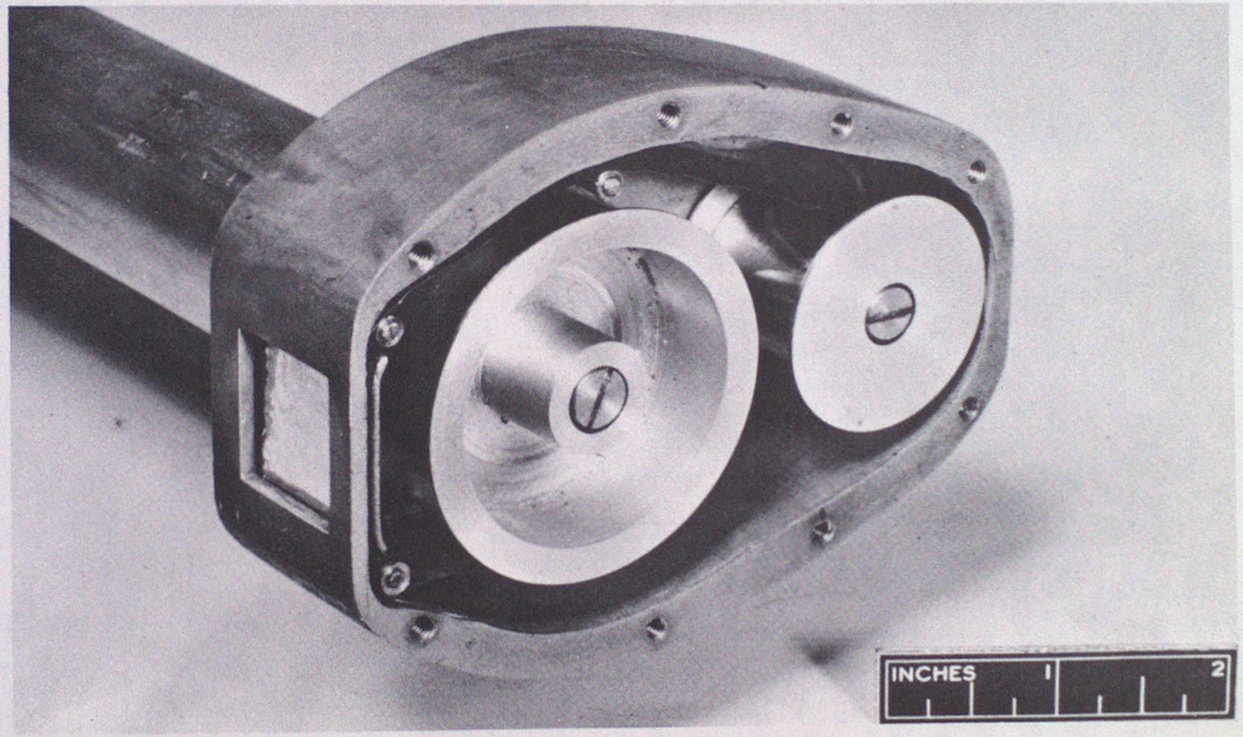
M.R.P. 1050

FIG. 4

ALUMINIUM TAPE

RAINDROP IMPACTOR





EXPOSED HEAD.

Nº MET. RES. FLT.
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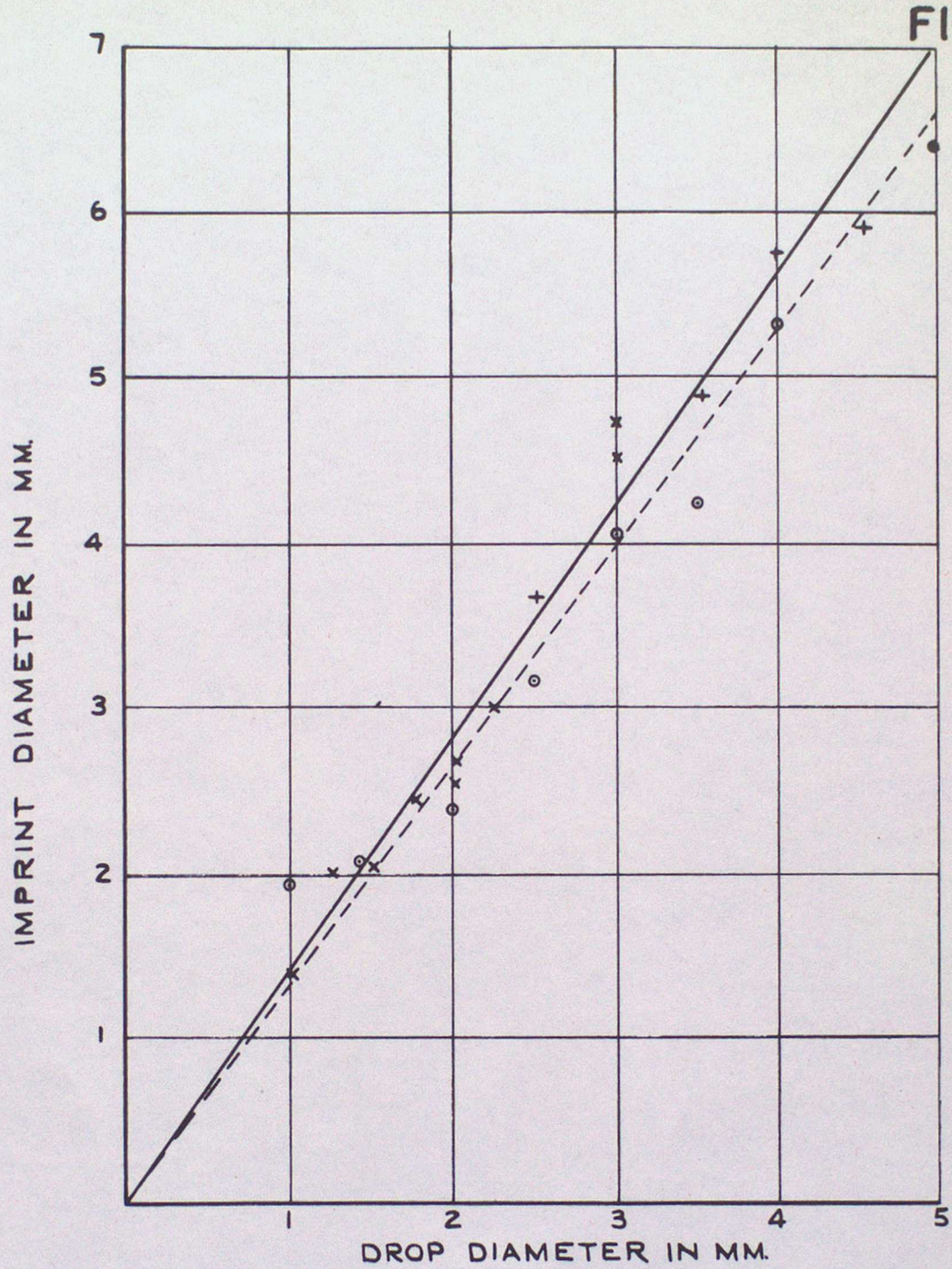
M.R.P. 1050

FIG.5



(REPRODUCED FROM T.N. M.E. 223.)

FIG. 5. CALIBRATION CURVE FOR ALUMINIUM FOIL (RAIN IMPACTOR GUN TESTS.)

M.R.P. 1050

FIG. 6

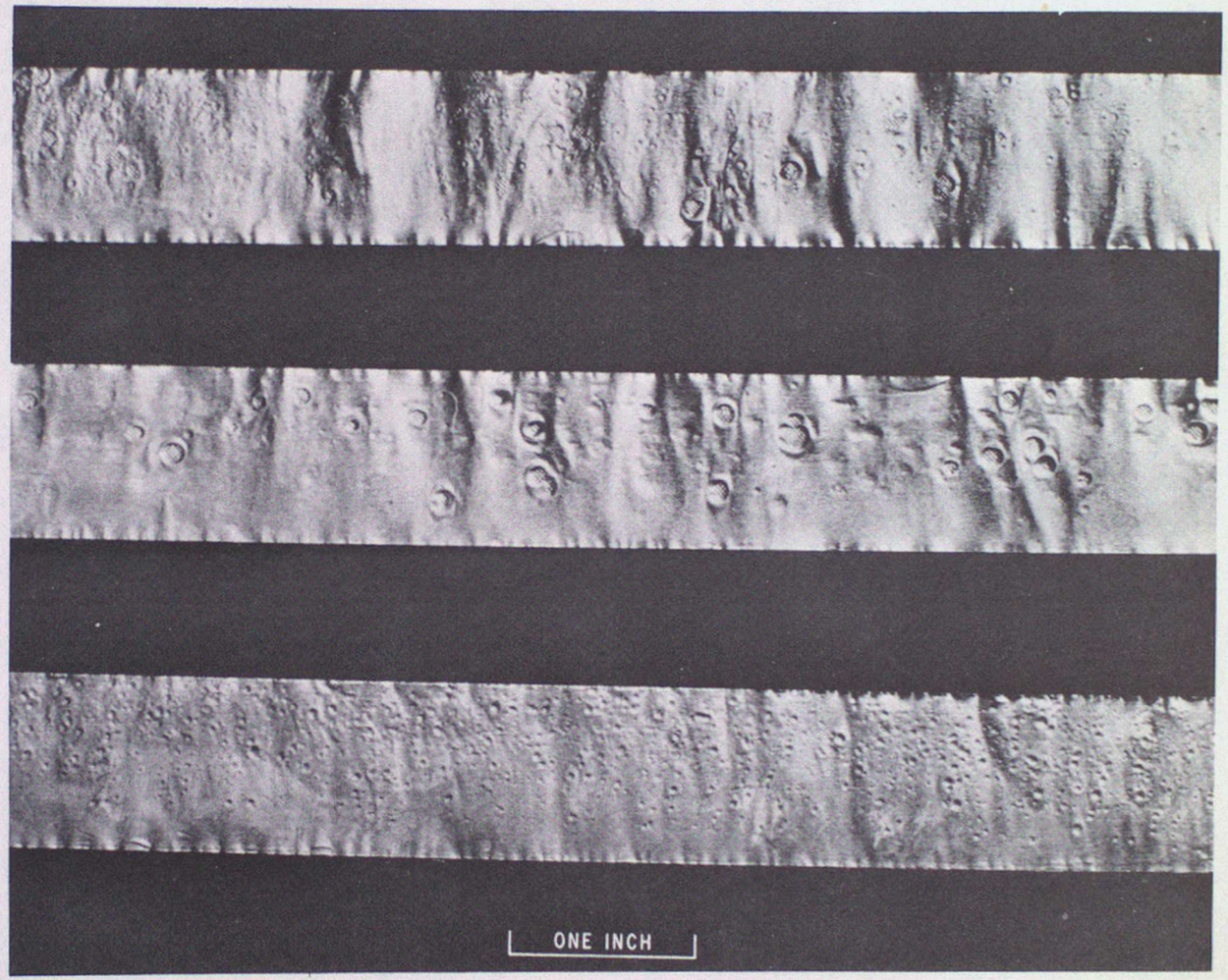
EXAMPLES OF PRECIPITATION

ON ALUMINIUM TAPE.

TOP MIXED RAIN AND SNOW.

CENTRE. RAIN.

BOTTOM. DRIZZLE.



M.R.P. 1050

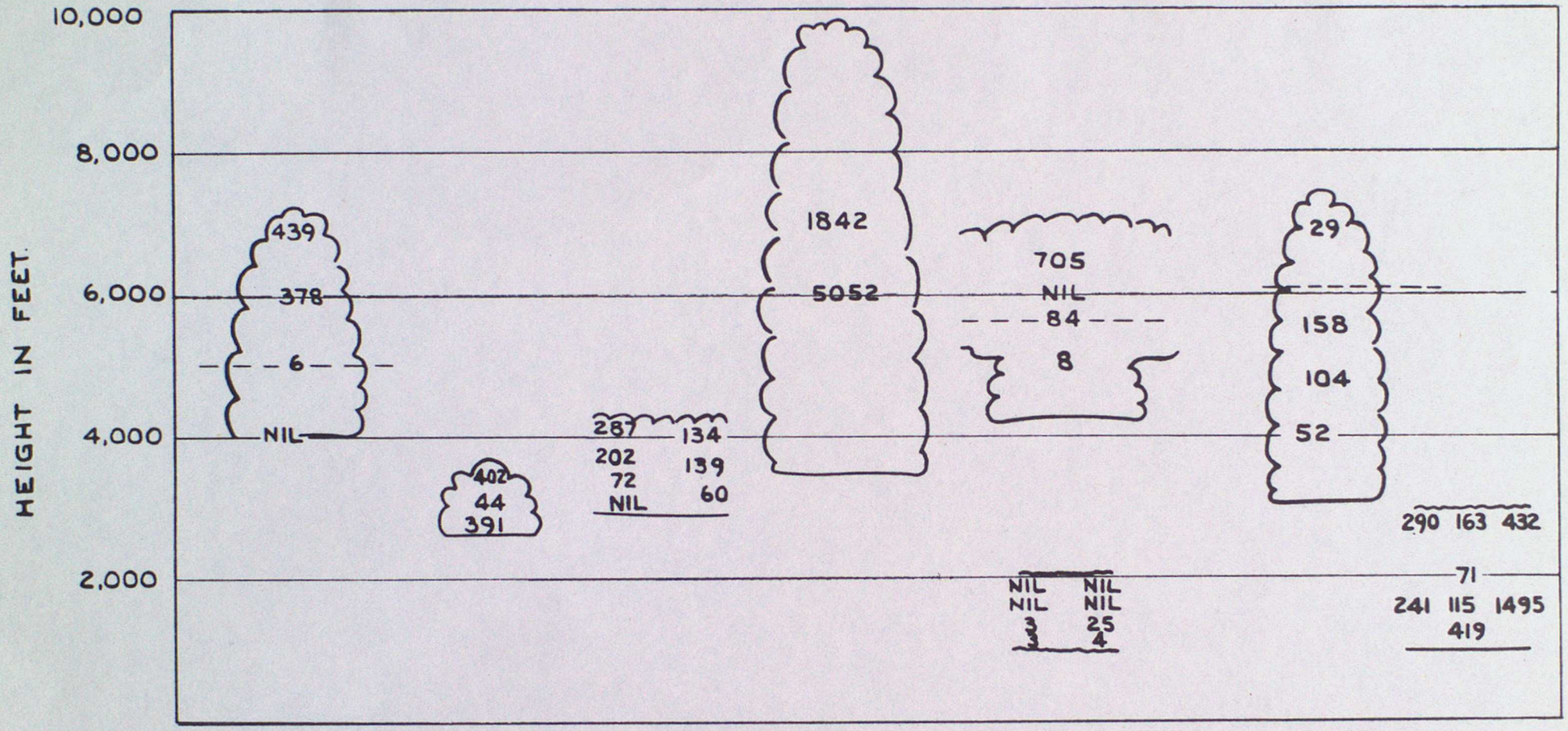


FIG. 7. EXAMPLES OF 100–250 MICRON DROP CONCENTRATIONS IN CUMULUS AND STRATOCUMULUS CLOUDS.

FIGURES GIVEN ARE NUMBERS PER CUBIC METRE.
FREEZING LEVEL DENOTED BY PECKED LINE WHERE APPLICABLE.

No MET. RES. FLT.
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TR. JS. 1.2.57
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FIG.7.

NIMBOSTRATUS	NIMBOSTRATUS	ALTOSTRATUS	CIRROSTRATUS
Date: 23.1.56 Situation: Cold front Portland-Yarmouth moving south-east. Low over S.North sea. Snow and rain sampled on or close to the front. Cloud top above 10000 feet. Base 2000 feet. Freezing Level 6000 feet.	Date: 11.12.56 Situation: Cold front from Devon to E.Anglia moving slowly south. Sampling of snow and rain in area of surface front. Cloud top above 15000 feet. Cloud base 4000 feet. Broken St. 1500 feet. Freezing Level 5500-6000 feet.	Date: 14.12.56 Situation: Warm front at midday, moving rapidly east, lying along a line Liverpool to Isle of Wight. Cloud sampled about 100 miles ahead of surface front. Cloud top not known. Cloud base 12000 feet approx.	Date: 12.12.56 Situation: At midday an active cold front from Liverpool to Scilly moving quickly east. Cloud sampled in a wide warm sector about 100 miles ahead of cold front. Cloud base 25000 feet. Top not known.
✳ 10000 feet 1 mm 15 -5°C 500 microns 80 250 microns 375 100 microns 425 ✳ 8000 feet 2 mm 20 -2.5°C 1 mm 200 500 microns 300 250 microns 400 100 microns 475 o✳ 6000 feet 3 mm 60 0°C 2 mm 50 1 mm 175 500 microns 125 250 microns 350 100 microns 12500 o 4000 feet 1½ mm 60 2.5°C 1 mm 125 500 microns 75 100-250 microns 75 o 2000 feet 2½ mm 7 6°C 2 mm 25 1½ mm 40 1 mm 80 500 microns 50 100-250 microns 150	✳ 6500 feet 1½ mm 30 -1°C 500 microns 150 100-250 microns 25000 o 5000 feet 1½ mm 25 1°C 1 mm 200 500 microns 350 100-250 microns 5500 o 2000 feet 2 mm 25 6°C 1½ mm 75 1 mm 175 100-250 microns 2000	✳ 20000 feet -20°C 250 microns 3500 100 microns 1500 ✳ 15000 feet -15°C 1 mm 150 500 microns 1000 250 microns 3000 100 microns 1500	✳ 26000 feet -35°C 250 microns 1000 100 microns 10000

FIG. 8. EXAMPLES OF SNOW AND RAIN IN LAYER CLOUDS.

✳ Snow o✳ Sleet o Rain

Sizes quoted are diameters in millimetres or microns
Figures quoted are numbers per cubic metre

M.R.P. 1050

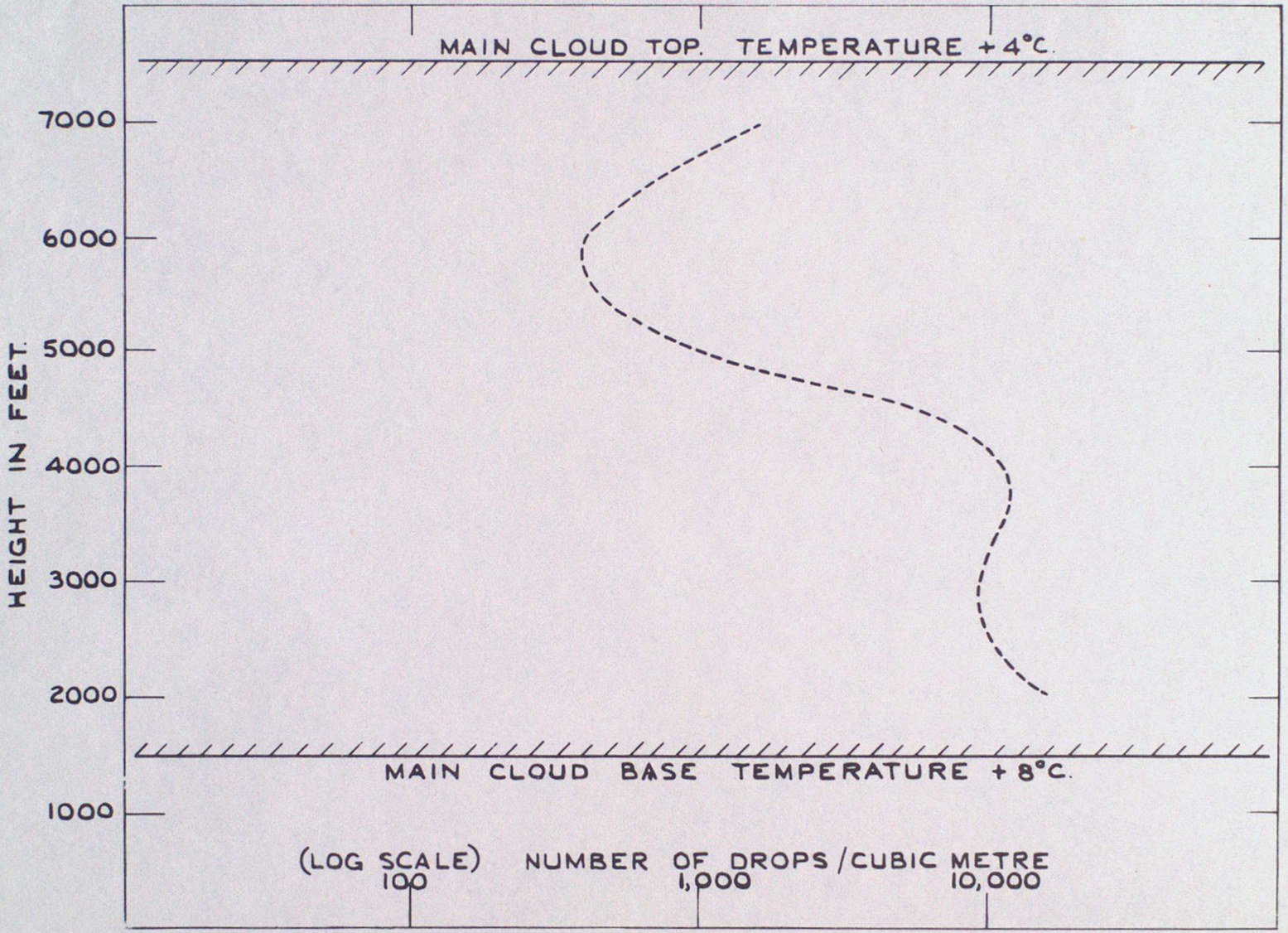

FIG. 9. VARIATION OF 100-250 MICRON DROPS WITH HEIGHT.

FARNBOROUGH. 1ST. AUGUST 1956.

No MET. RES. FLT.
DR
TR 15.4.2.57
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APP.

FIG. 9.

M.R.P. 1050

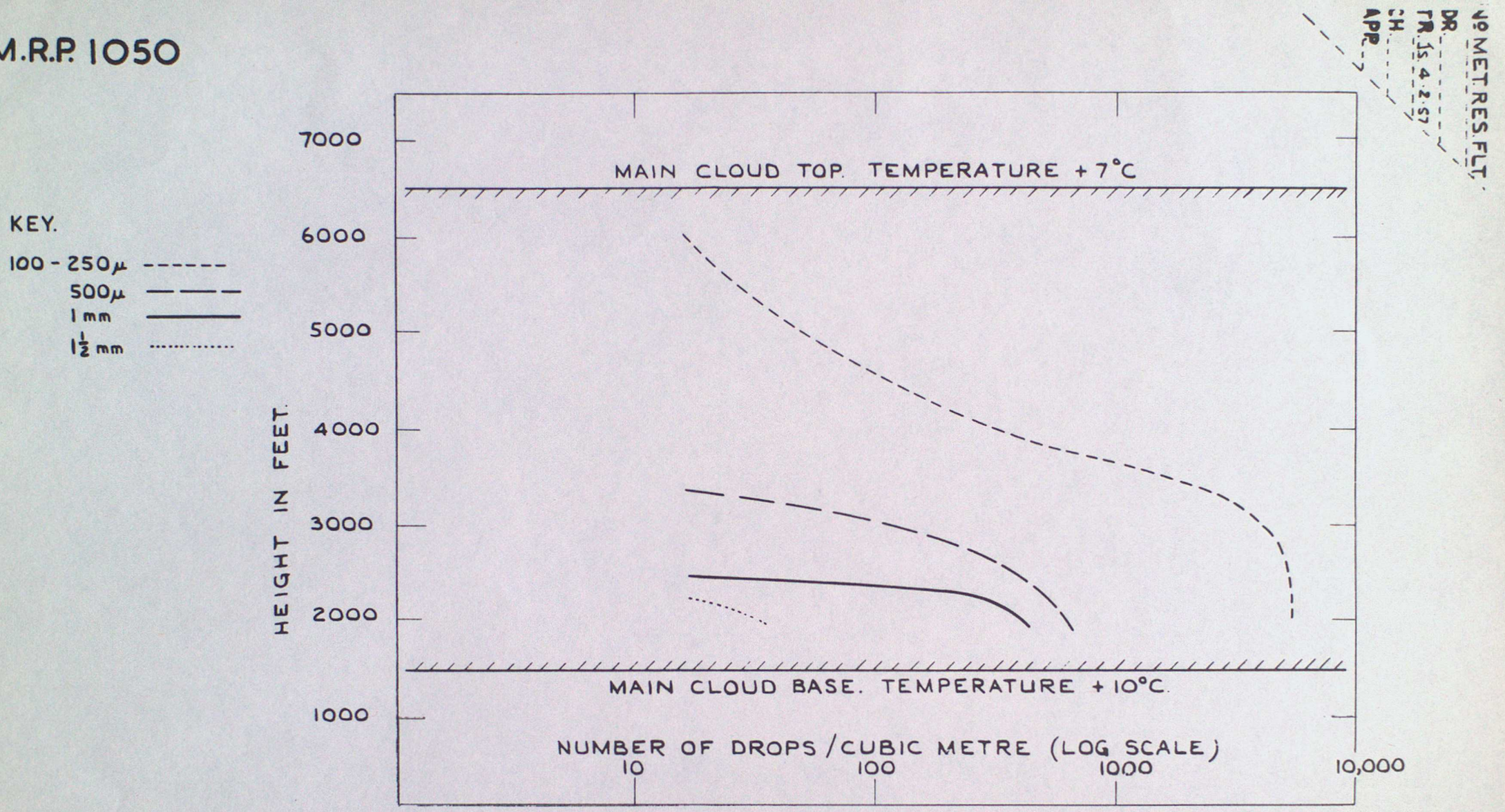

FIG. 10. VARIATION OF RAINDROP SPECTRUM WITH HEIGHT.

FARNBOROUGH 20th JULY 1956.

FIG. 10.

M.R.P. 1050

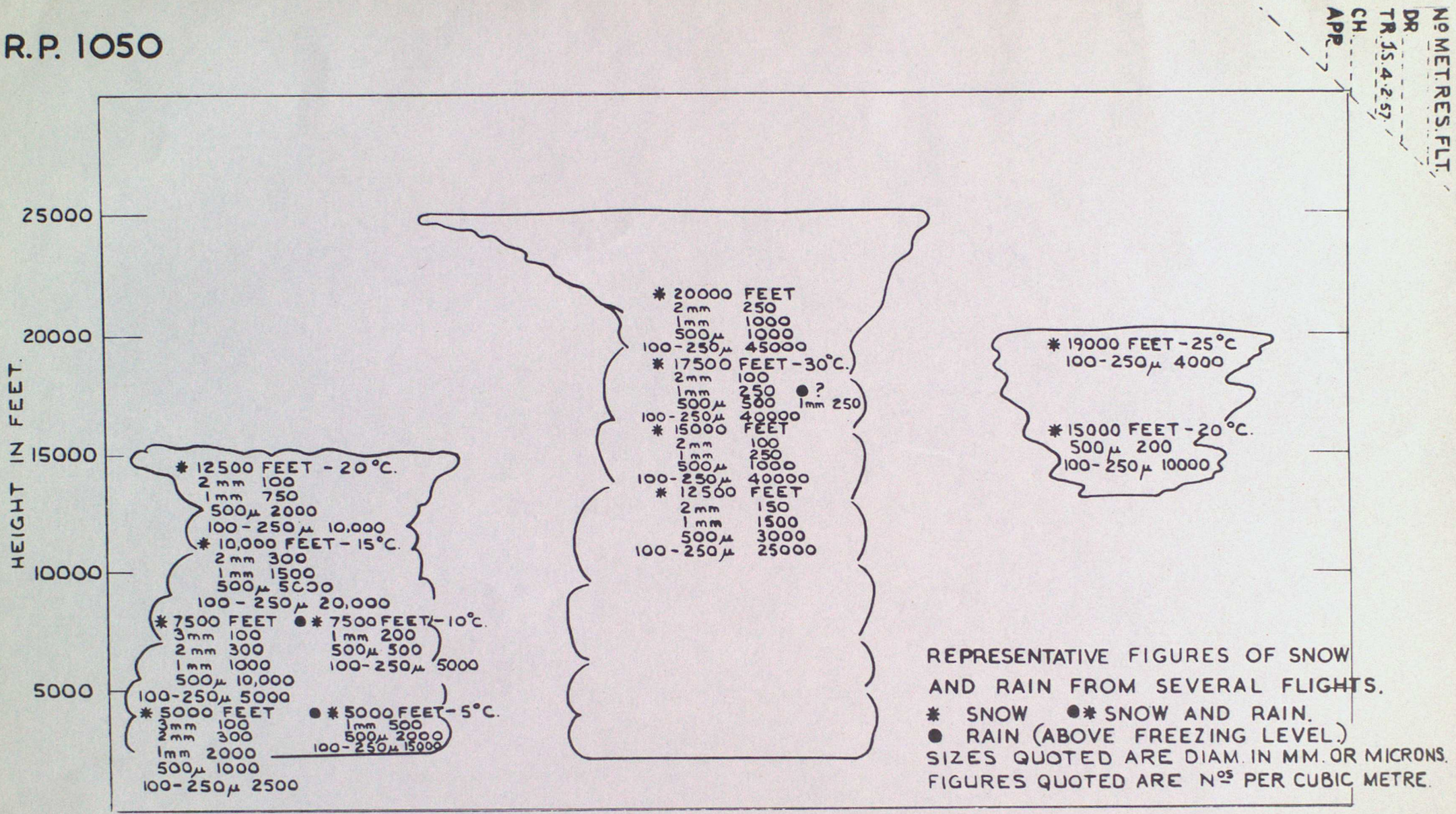

FIG. II. CUMULONIMBUS CLOUD.

FIG. II.

No MET. RES. FLT.
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